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MSC GEODETIC ENGINEERING

MSR-02: ADVANCED TECHNIQUES FOR MOBILE SENSING AND ROBOTICS (GEODESY TRACK)

05: FROM IMAGES TO POINT CLOUDS (SFM)

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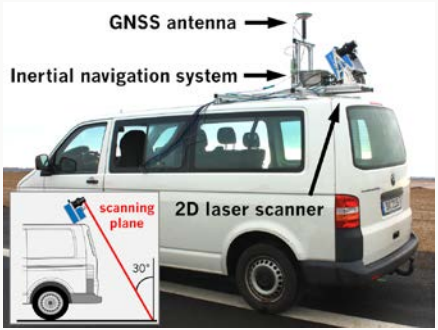
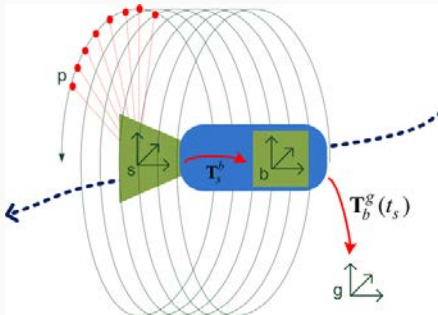
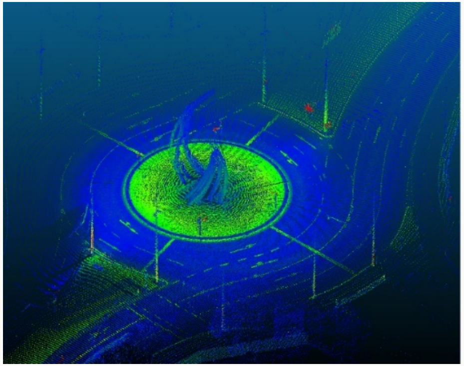
UNIVERSITY OF BONN

ADVANCED TECHNIQUES FOR MOBILE SENSING AND ROBOTICS – LECTURE CONTENT

SO FAR: MOBILE LASER SCANNING



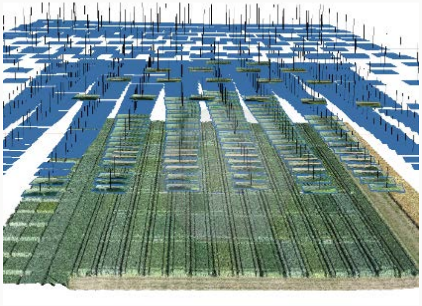




$$\mathbf{p}_{object}^{global}(t_s) = \mathbf{T}_{body}^{global}(t_s) \cdot \mathbf{T}_{sensor}^{body} \cdot \mathbf{p}_{object}^{sensor}(t_s)$$

$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e(L,B)\,\mathbf{R}_b^n(\phi,\theta,\psi) \cdot \left[\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \mathbf{R}_s^b(\alpha,\beta,\gamma) \cdot \begin{bmatrix} 0 \\ d \cdot \sin b \\ d \cdot \cos b \end{bmatrix} \right]$$

NOW:
WHAT IF THE THE SENSOR IS A CAMERA?



$$\mathbf{p}_{object}^{global}(t_s) = \mathbf{T}_{body}^{global}(t_s) \cdot \mathbf{T}_{sensor}^{body} \cdot \mathbf{p}_{object}^{sensor}(t_s)$$

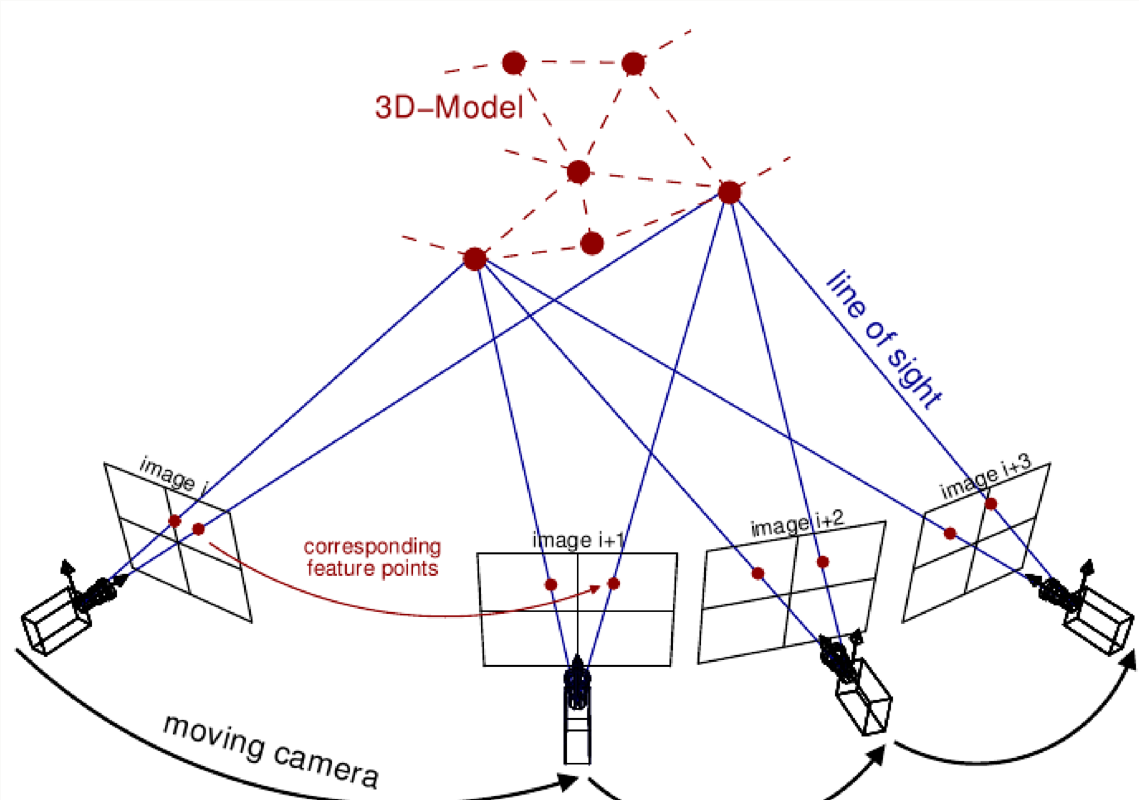
3D world coordinate

?

2D image coordinate

We can not calculate a 3D position of an object from a single camera observation. What to do?

STRUCTURE FROM MOTION/MULTI-VIEW STEREO



http://www.theia-sfm.org/sfm.html

LINK TO STACHNISS' LECTURE

Cyrill Stachniss: Lecture ‚Direct Linear Transform: Camera Calibration and Localization'

Now:

Estimate

- Intrinsics
- Extrinsics
- Object Points

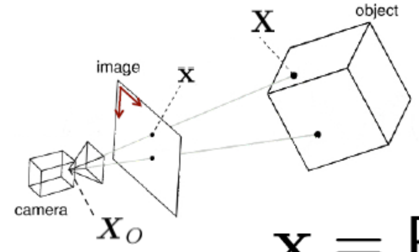
from multiple images

No detailed photogrammetric + mathematical background in this lecture!

Focus on UAV mapping

Mapping (Recap)

Direct linear transform (DLT) maps any object point $\mathbf{X}$ to the image point $\mathbf{x}$



$$\mathbf{x} = \mathsf{P}\mathbf{X}$$

$$\mathbf{x} = KR[I_3 | -X_O]\mathbf{X}$$

observed image point

c, s, m, x_H, y_H

3 rotations

3 translations

control point coordinates (given)

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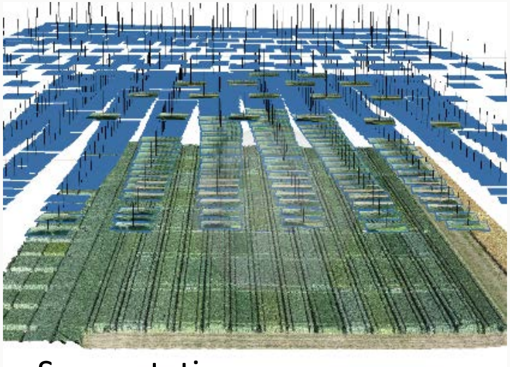
DEFINITIONS FROM FÖRSTNER'S BOOK

$$f'_{it} = \mathcal{P}_t(\mathcal{F}_i; \mathcal{O}_t, \mathcal{C}_t)$$



Scene static, camera moves

Camera **calibration** parameters (at times t)

Set of **orientations** (at times t) → ‚**motion**'

Set of **feature points** in object space →‚**structure**'

Set of **feature points** in image space (‚image features')

Wolfgang Förstner, Bernhard P. Wrobel: Photogrammetric Computer Vision, Springer

DEFINITIONS FROM FÖRSTNER'S BOOK

$$f'_{it} = \mathcal{P}_t(\mathcal{F}_i; \mathcal{O}_t, \mathcal{C}_t)$$

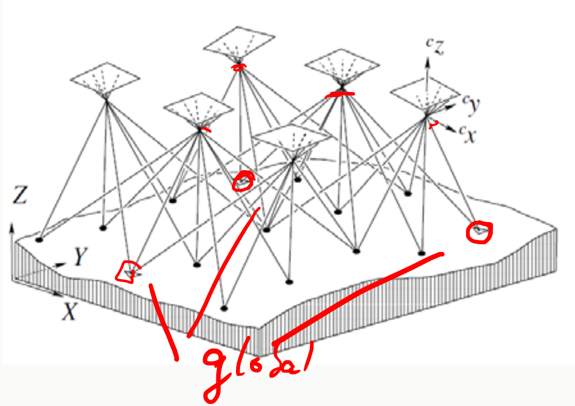
- **Orientation** or **motion from structure:**
  ➔ get $\{O_i\}$ from correspondences $\{F_i, f_{it}\}$
- **Calibration:**
  ➔ get C_t from $\{f_{it}\}$ and possibly given $\{F_i\}$
- **Reconstruction** or **structure from motion (SfM):**
  ➔ get $\{F_i\}$ from $\{f_{it}\}$
- **Relative Orientation**:
  ➔ get relative pose between multiple images and a **local** scene description $\{F_i\}$ from corresponding
  image points $\{f_{i\_a}, f_{i\_b}, f_{i\_c}, \ldots\}$ in multiple images a, b, c, …
- **Absolute Orientation:**
  ➔ get **global** scene $\{F_i\}$ from **local** scene $\{F_i\}$ and 3D control features

Wolfgang Förstner, Bernhard P. Wrobel: Photogrammetric Computer Vision, Springer

DEFINITIONS FROM FÖRSTNER'S BOOK

$$f'_{it} = \mathcal{P}_t(\mathcal{F}_i; \mathcal{O}_t, \mathcal{C}_t)$$

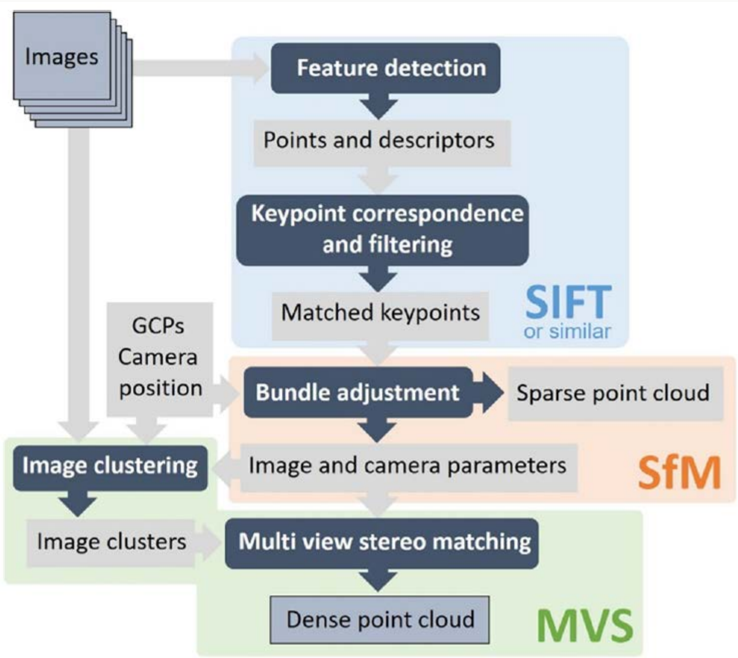
- **Bundle Adjustment (BA):**
  ➔ get $\{F_i\}$ and $\{O_i\}$ and C_t from $\{f_{it}\}$
  ➔ **global** $\{F_i\}$ also needs
  3D control features or
  direct measurements of
  some points/poses (e.g. via GNSS)
  ➔ combines all points above
  ➔ closely related to SLAM

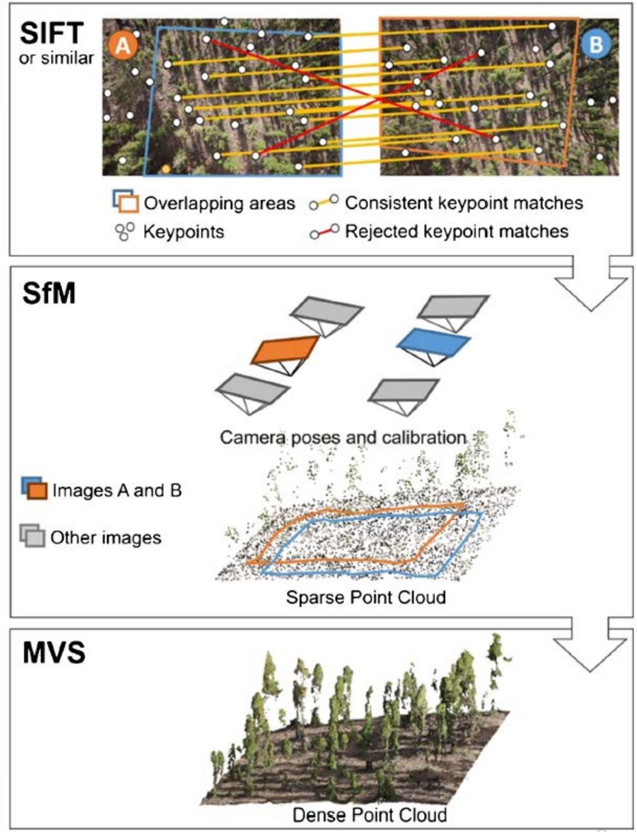


- What most people actually mean when they say **SfM**:
  ➔ The above BA including all necessary steps to create the initial solution (relative orientation, sequentially adding images to create an image block, not necessarily scaled and in absolute coordinates)
  ➔ Result: **Sparse point cloud** $\{F_i\}$ & image parameters $\{O_i\}$, C_t

Wolfgang Förstner, Bernhard P. Wrobel: Photogrammetric Computer Vision, Springer

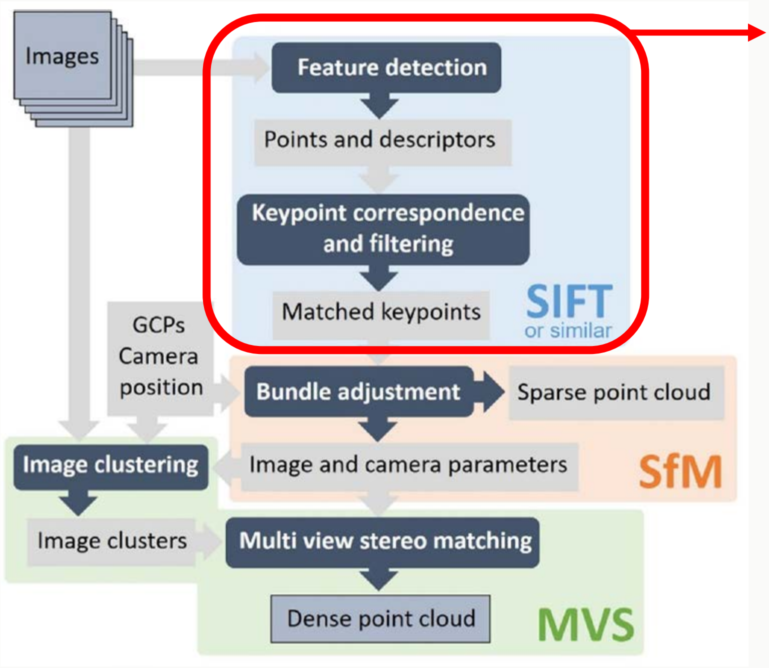
SFM/MVS WORKFLOW





From: Iglhaut, J., Cabo, C., Puliti, S. et al. Structure from Motion Photogrammetry in Forestry: a Review. Curr Forestry Rep 5, 155–168 (2019). https://doi.org/10.1007/s40725-019-00094-3

SIFT OR SIMILAR



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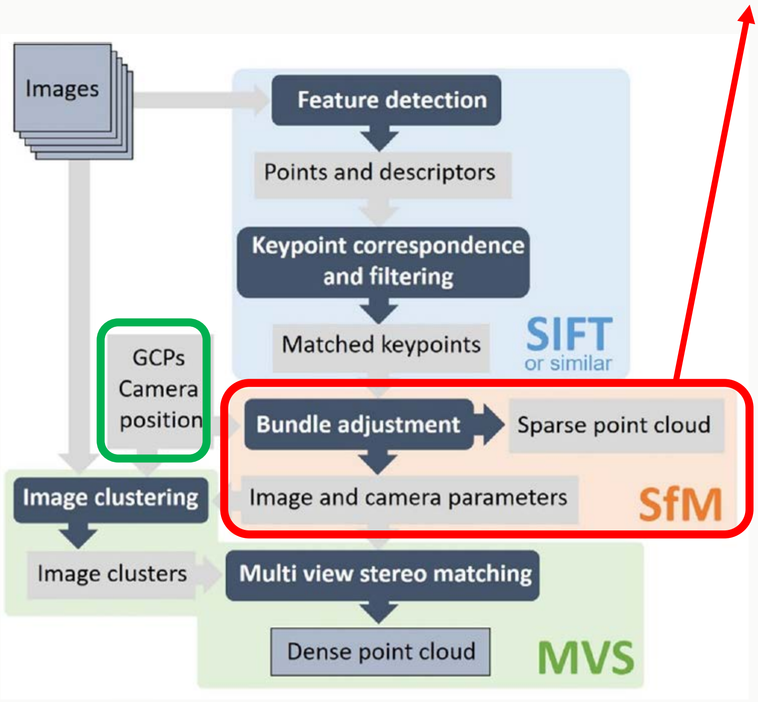
1. Extract features
   - SIFT, SURF, BRISC, …
   - Corner or Blob Features
   - Also multi-scale approaches
2. Feature description
   - Vector of numbers describing gradients, intensities, …
3. Feature Matching
   - Finding the same features in multiples images
   - Outlier rejection

STRUCTURE FROM MOTION (SFM)



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1. Initialize
   - use two images
   - Initialize structure
2. Add new images
   - Orient new image using existing structure
   - Run local BA
   - Initialize new structure points
3. Optional: Georeferencing
   - Include information from GPS or Ground control points
4. Run final BA on complete image block

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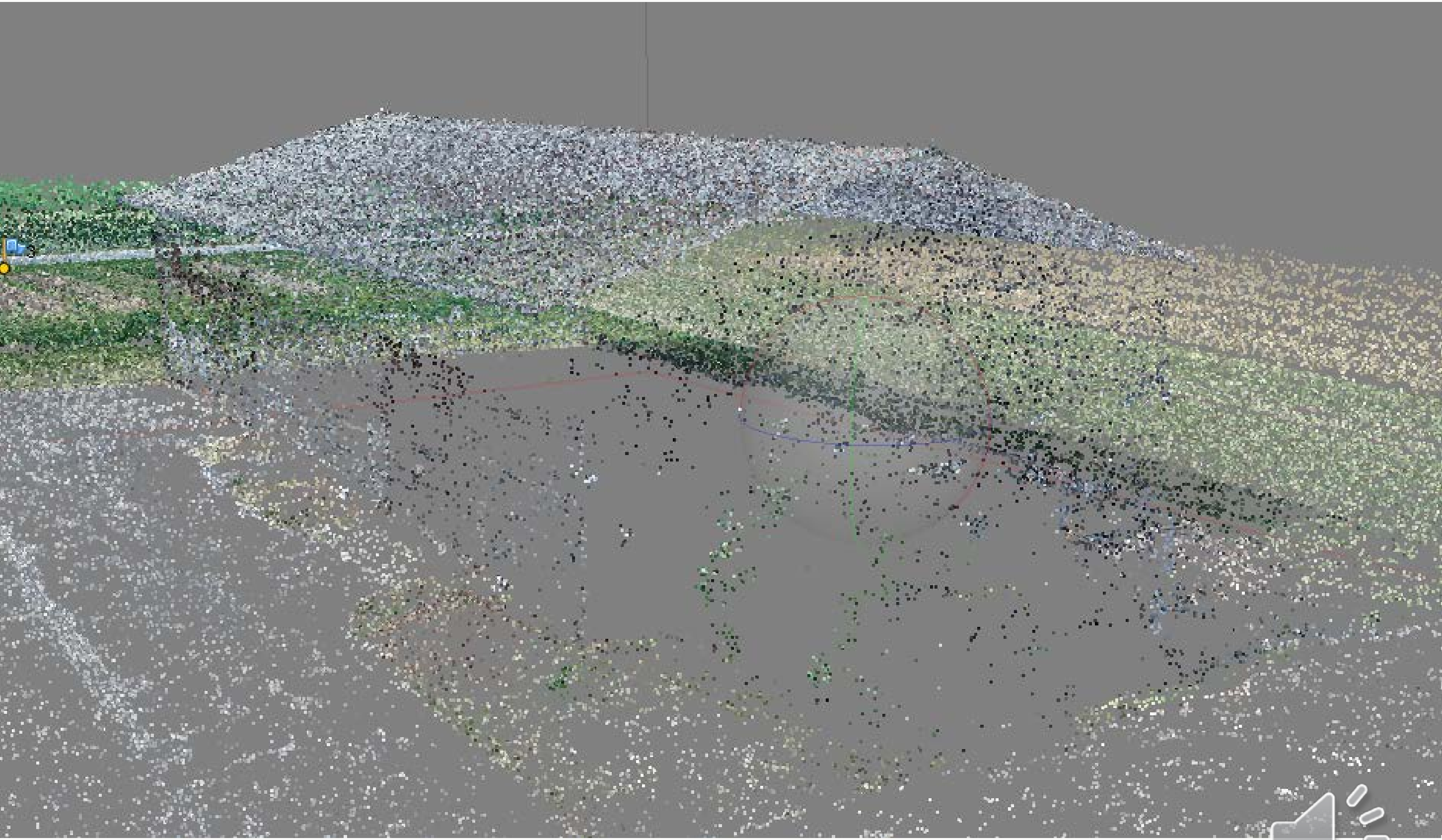
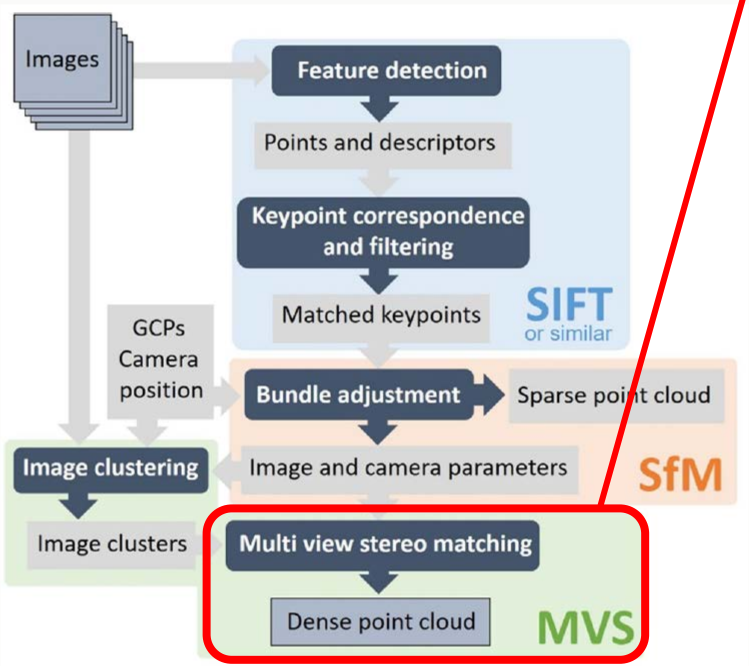
SPARSE POINT CLOUD



MULTI VIEW STEREO (MVS)



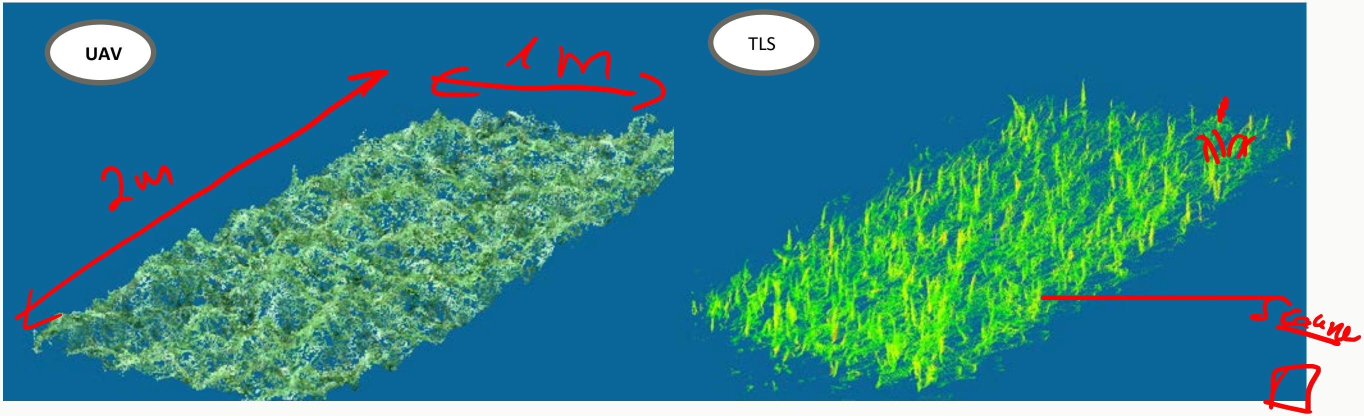
From: Iglhaut, J., Cabo, C., Puliti, S. et al. Structure from Motion Photogrammetry in Forestry: a Review. Curr Forestry Rep 5, 155–168 (2019). https://doi.org/10.1007/s40725-019-00094-3

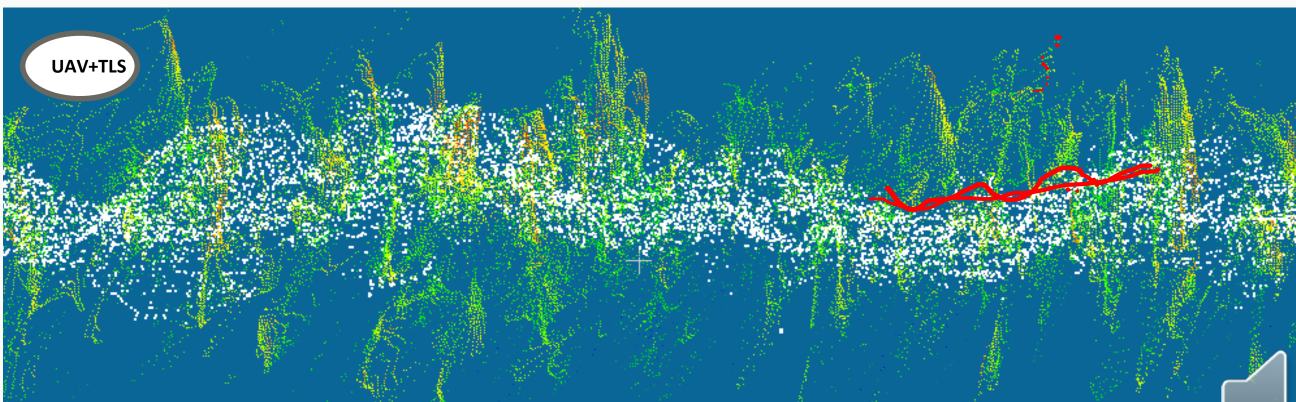
- Try to find much more correspondences between images than using features
- Ideal case: match every pixel
- Match **areas** instead of **features**
- Use **known orientations** and epipolar constraints
- Use multi-resolution
- Use multi-image matching
- Use assumptions on surface smoothness (semi-global matching)

➔ Result: **dense cloud**

DENSE POINT CLOUD

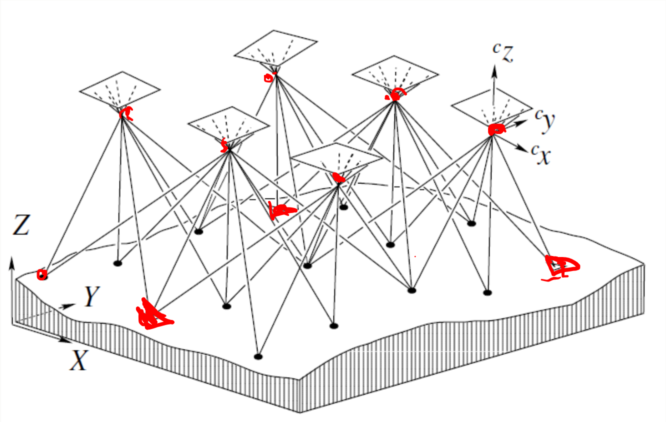
IMAGE BASED (UAV) VS LASER BASED (TLS)





GEOREFERENCING

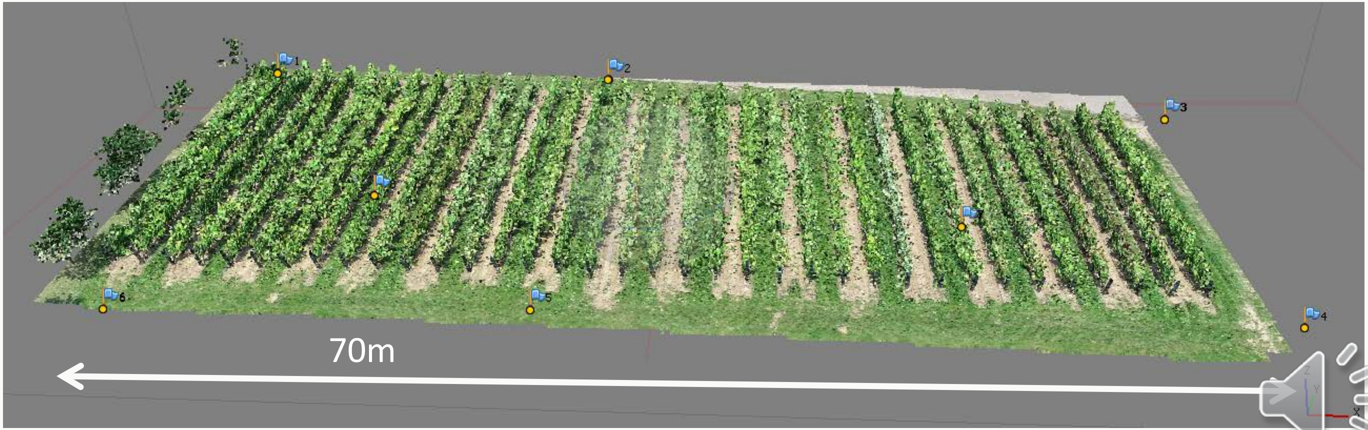
- Georeferencing is needed
  - o to get a scale OR
  - o to get the scene in a global coordinate system



- Option 1: Use known scene points (ground control points or 3D control features) to absolutely orient all images and the scene (**indirect georeferencing,** ‚classical‘ case)
- Option 2: Use onboard sensors to absolutely orient images and skip SfM step (**direct georeferencing,** rarely used)
- Option 3: Combine 1+2 (**integrated sensor orientation,** often used)

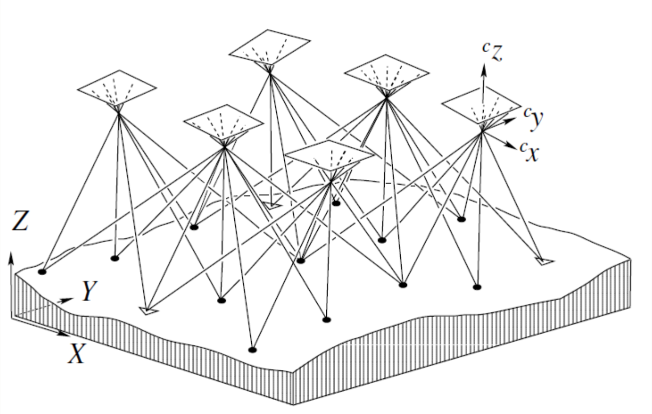
INDIRECT GEOREFERENCING

- Deploy a set of Ground Control points and measure their coordinates
- Use total stations: ~mm accuracy
- Use RTK GNSS: ~1-3cm accuracy



DIRECT GEOREFERENCING & INTEGRATED SENSOR ORIENTATION

- Determine the **camera orientation** (position and rotation parameters) at the **time** when the image was taken



- We need:
  - A system/algorithm to determine the position and orientation of the UAV ➔ lecture **Trajectory estimation**
  - The relative orientation (rotation and translation) between the UAV and the camera ➔ lecture **System calibration**
  - The exact time (syncronized with trajectory estimation), when the image was taken ➔lecture **Sensor Synchronization**

UAV NAVIGATION SENSORS

STANDARD UAV SENSORS

- Low-Cost Inertial sensors for in-flight stability control
- Low-cost code based GNSS (~several meters accuracy)
- Sensors used for navigation and mission control
- Sensors can also be used for image tagging (**time-sync** and **calibration** is not critical as accuracy is anyway ~m)
- Needs ground control points for precise **indirect georeferencing**

UAV NAVIGATION SENSORS

ON-BOARD RTK GNSS

- More and more commercial solution are available
- Real-time solution needs connection for correction data, otherwise offline processing
- **Time-sync** and **calibration** becomes critical, most solution work only with certain cameras
- RTK GNSS mostly used only for image tagging not for navigation
- High precision Image coordinates can then be integrated in the Bundle Adjustment (**integrated sensor-orientation**)

Mavinci Sirius Pro

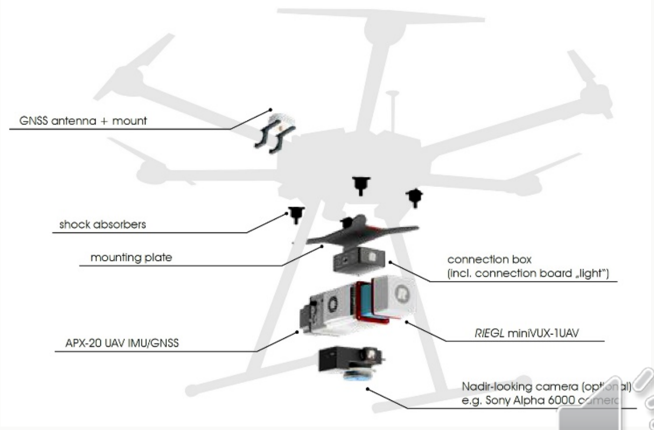
SenseFly eBee RTK

DJI Phantom 4 RTK

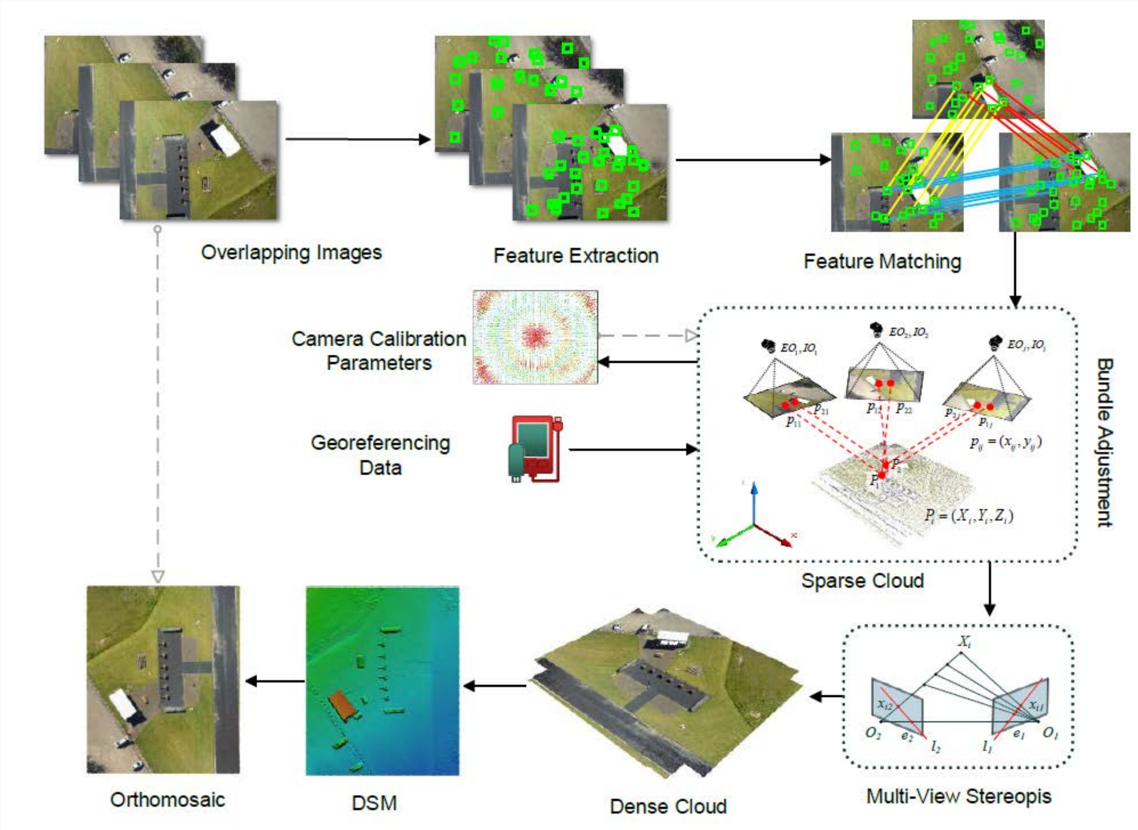
UAV NAVIGATION SENSORS

HIGH-END IMU/GNSS RECEIVER

- High-end IMU/GNSS usually used for **direct georeferencing** of laser scans
- Same principle as in mobile laser scanning



SUMMARY SFM PIPELINE



From: Farid Javadnejad. Small Unmanned Aircraft Systems (UAS) for Engineering Inspections and Geospatial Mapping, PhD Thesis, Oregon State University, 2018

SFM SOFTWARE
(NO RANKING, NOT TESTED, NO GUARANTEE)

- Free
  - Visual SFM
  - Bundler + PMVS2
  - OSM-Bundler
  - MicMac
  - Meshroom
  - SF3M
  - …
- Commercial solutions
  - Agisoft Metashape
  - Pix4D
  - Reality Capture
  - DroneDeploy
  - Photomodeler
  - …
- Google and find more

PROJECT EXAMPLE:
DFG RESEARCH GROUP: MAPPING ON DEMAND

- **Goal:** Lightweight Unmanned Aerial Vehicle based 3D reconstruction of objects and environments

Example scenario:

modified, www.wikipedia.org

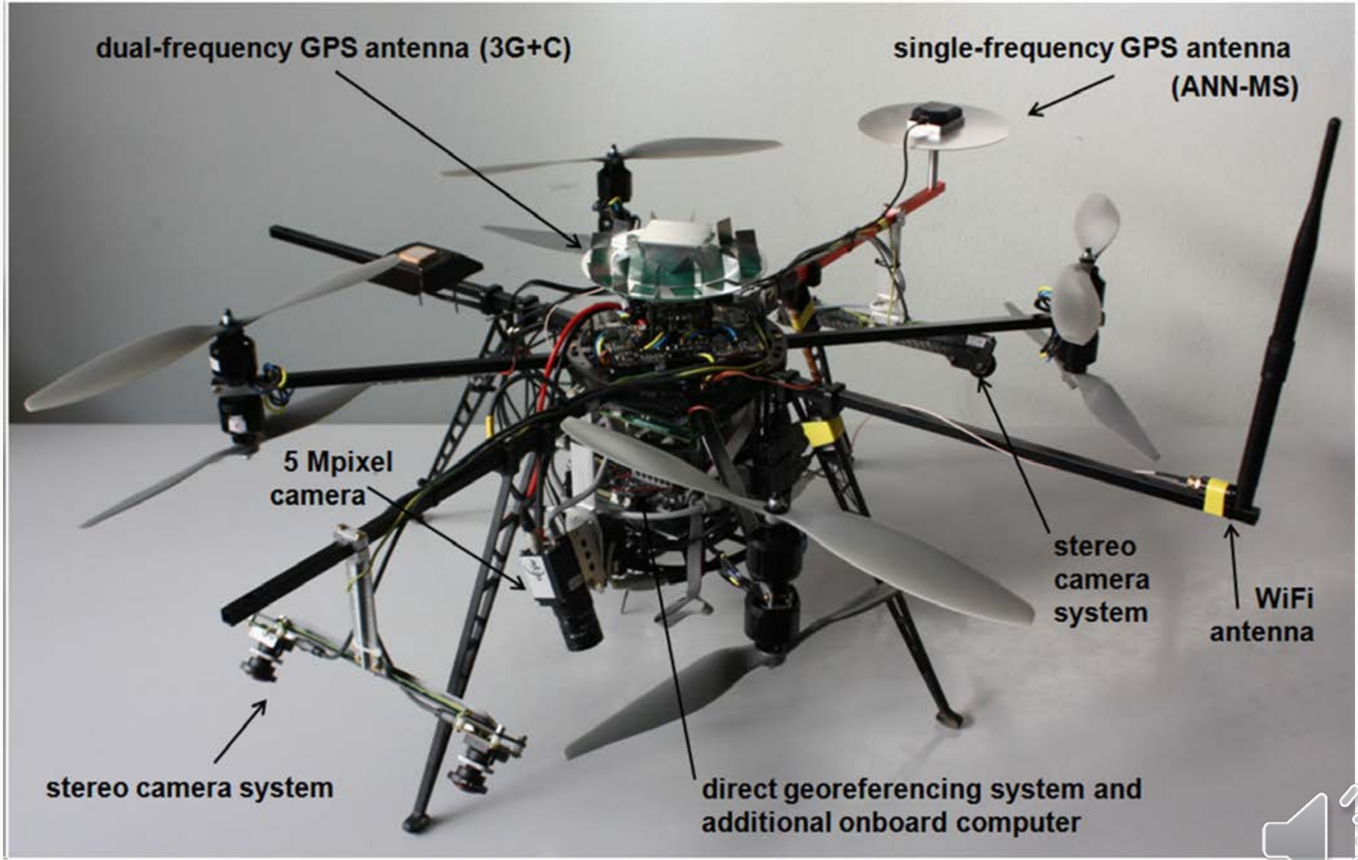
- Based on a **semantic** user request (e.g. ‚find all open windows!‘)
- On demand (**no preparation** of the environment)
- In **Realtime** (ideally no offline processing)
- Fully **autonomous** flight (trajectory planning, collision avoidance)
- Interpretation of facade elements

Project started in 2012 and finished in 2019

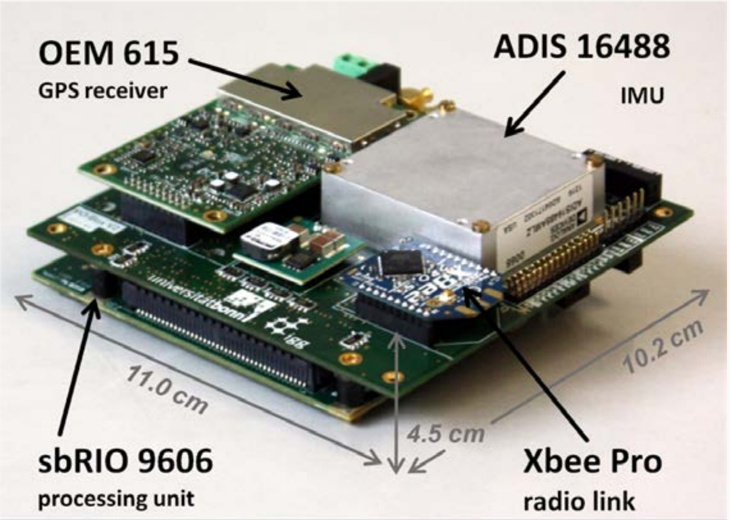
MAPPING ON DEMAND: SUB-PROJECTS

- **Real-time Pose Determination**
  (Uni Bonn, Inst. of Geodesy and Geoinformation, Geodesy)
- **Incremental Mapping and Exploration**
  (Uni Bonn, Inst. of Geodesy and Geoinformation, Photogrammetry)
- **Local Perception and Obstacle Detection**
  (Uni Bonn, Inst. of Computer Science, Intelligent Autonomous Systems)
- **3D Surface Reconstruction**
  (TU München, Inst. of Computer Science, Computer Vision)
- **Representation and Generation of 3D and 4D Maps**
  (Uni Bonn, Inst. of Computer Science, Computer Graphics)
- **Semantic Building Models**
  (Uni Bonn, Inst. of Geodesy and Geoinformation, Geoinformation)

CUSTOM UAV


dual-frequency GPS antenna (3G+C)
single-frequency GPS antenna (ANN-MS)
5 Mpixel camera
stereo camera system
WiFi antenna
stereo camera system
direct georeferencing system and additional onboard computer

CUSTOM GEOREFERENCING SYSTEM



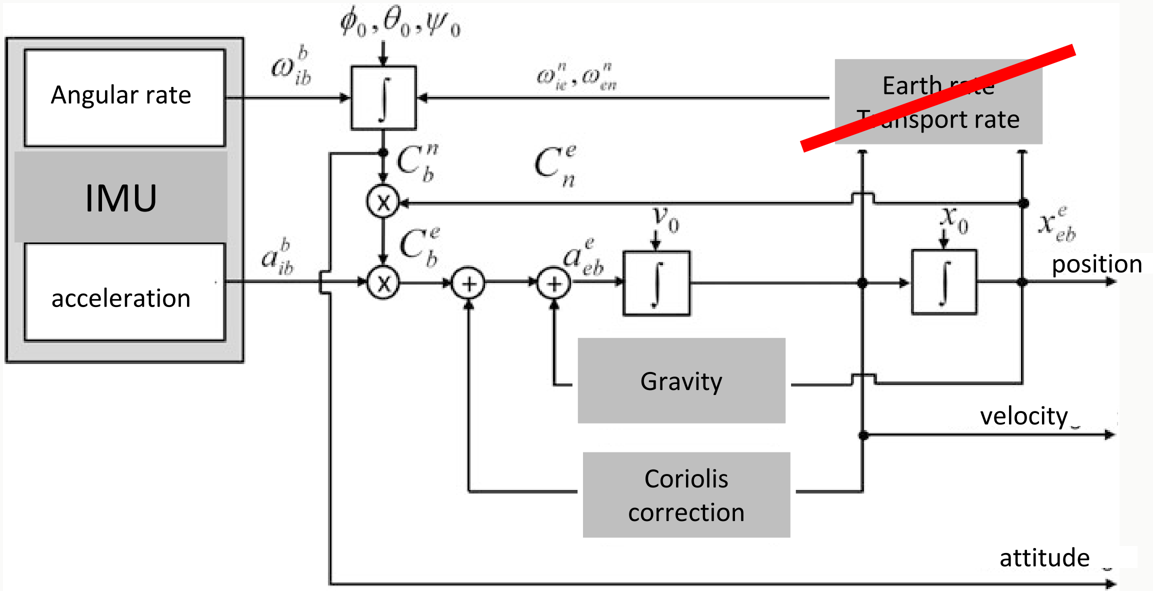
Sensors

- 3 axis accelerometer
- 3 axis angular rate sensor
- 3 axis magnetometer
- barometer
- dual frequency GPS receiver
- single frequency GPS receiver
- radio link for GPS correction data
- input for external sensors (e.g. stereo cameras)

- small size, small weight (~400g including antennas)
- real-time (!) processing of position and orientation
- high accuracy (~1cm, <1°)
- custom multi sensor fusion algorithms for high robustness
- high flexibility (use with any other mobile multi-sensor system)

TRAJECTORY ESTIMATIOPN /KALMAN FILTER

SIMPLIFIED INERTIAL NAVIGATION

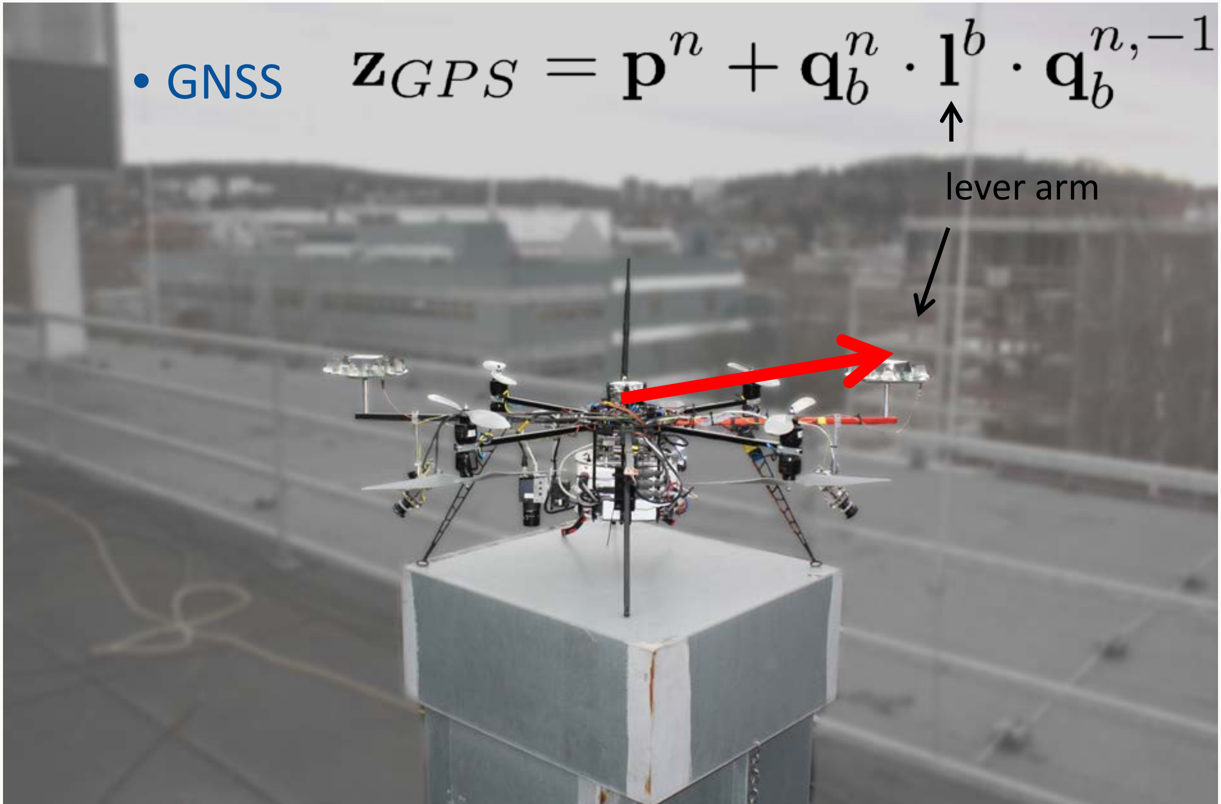


$$\begin{pmatrix}\mathbf{q}_b^n\\ \mathbf{p}_{eb}^e\\ \mathbf{v}_{eb}^n\end{pmatrix}_k = f\left(\begin{pmatrix}\mathbf{q}_b^n\\ \mathbf{p}_{eb}^e\\ \mathbf{v}_{eb}^n\end{pmatrix}_{k-1}, \begin{pmatrix}\mathbf{a}_{ib}^b\\ \boldsymbol{\omega}_{ib}^b\end{pmatrix}_{k-1}\right)$$

KALMAN FILTER

MEASUREMENT MODELS

- GNSS $\mathbf{z}_{GPS} = \mathbf{p}^n + \mathbf{q}_b^n \cdot \mathbf{l}^b \cdot \mathbf{q}_b^{n,-1}$

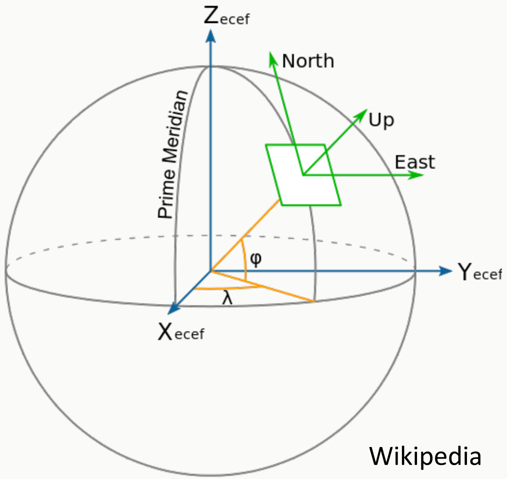


KALMAN FILTER

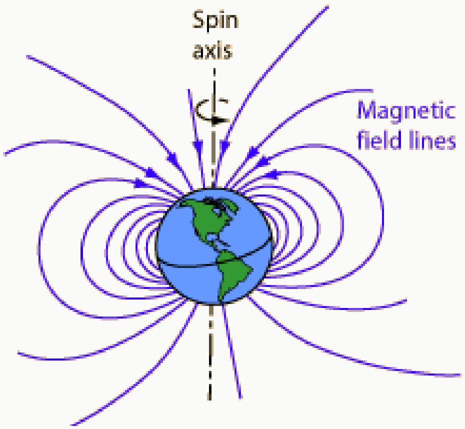
MEASUREMENT MODELS

- Earth magnetic field

$$\mathbf{z}_{mag} = \mathbf{q}_b^{n,-1} \cdot \mathbf{b}_{earth}^{n} \cdot \mathbf{q}_b^{n}$$



Wikipedia



KALMAN FILTER

MEASUREMENT MODELS

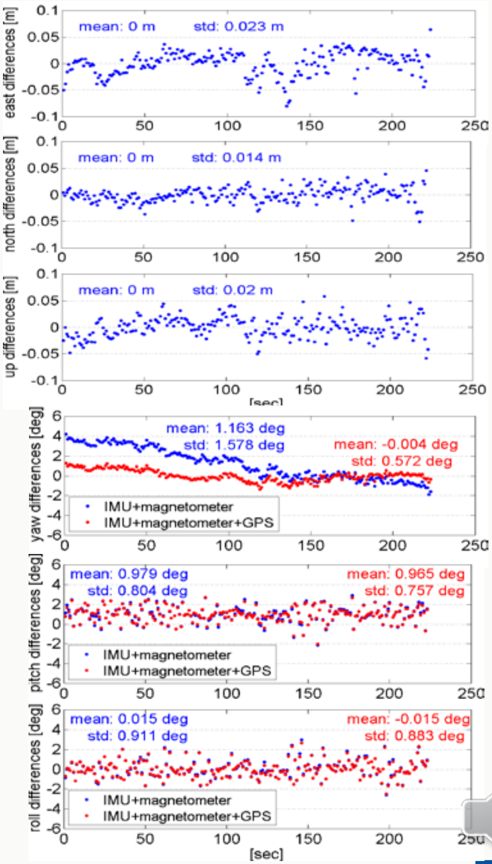
- Local GNSS Baseline

$$\mathbf{z}_{base} = \mathbf{q}_n^b \cdot \mathbf{l}_{base}^b \cdot \mathbf{q}_n^{b,-1}$$

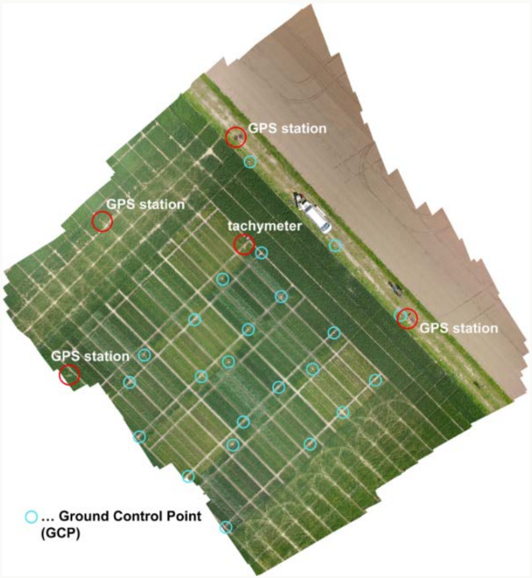
GNSS baseline

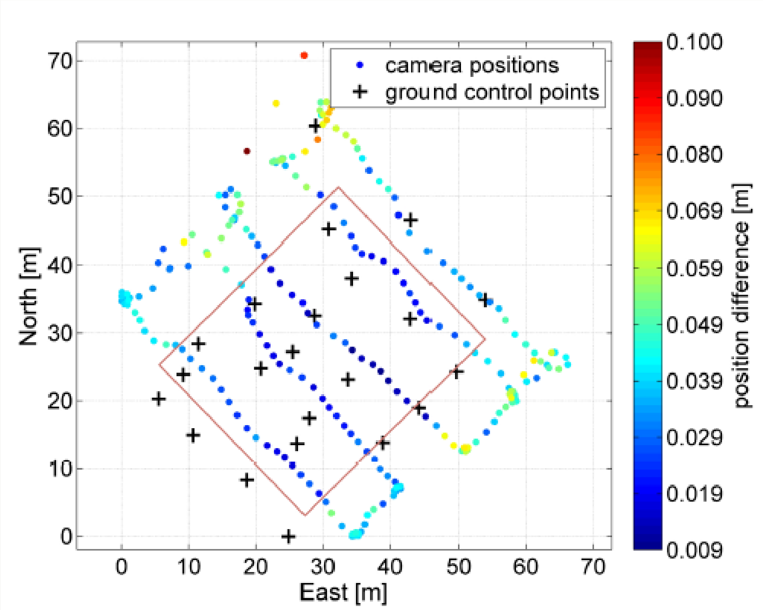
ACCURACY ANALYSIS I

- Acquisition of images @1Hz
- Onboard camera pose estimation using direct georeferencing system
- offline bundle adjustment to estimate camera poses based on images
- Comparision of both trajectories (up to a 7 parameter transformation)



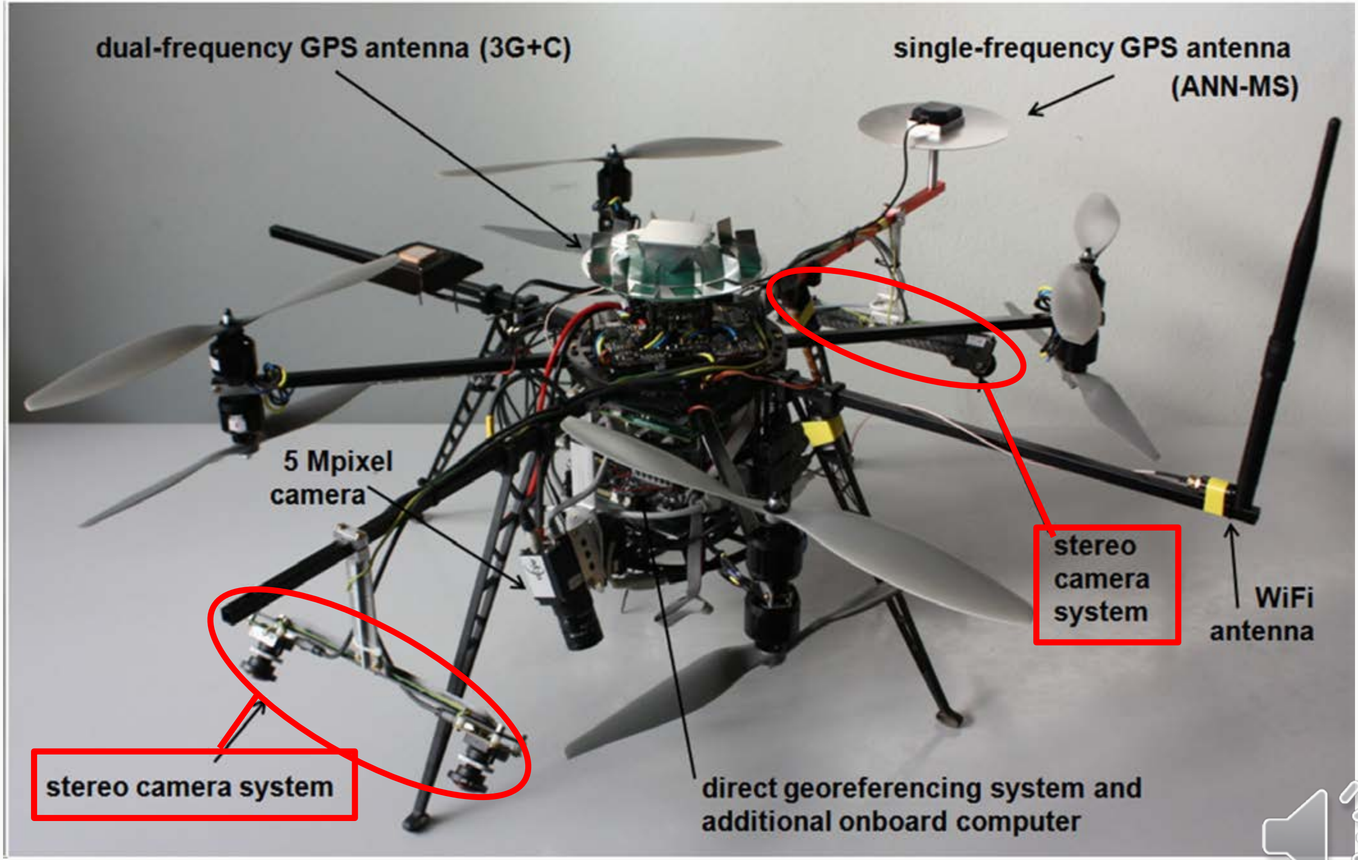
ACCURACY ANALYSIS II



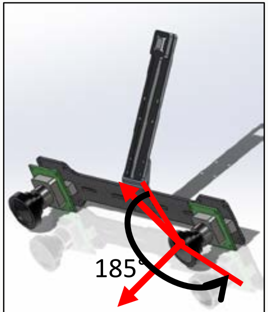


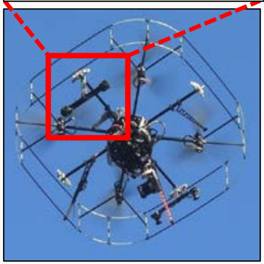
Difference between the camera positions as measured by onboard RTK and as determined using GCPs and photogrammetry ➔ ~cm

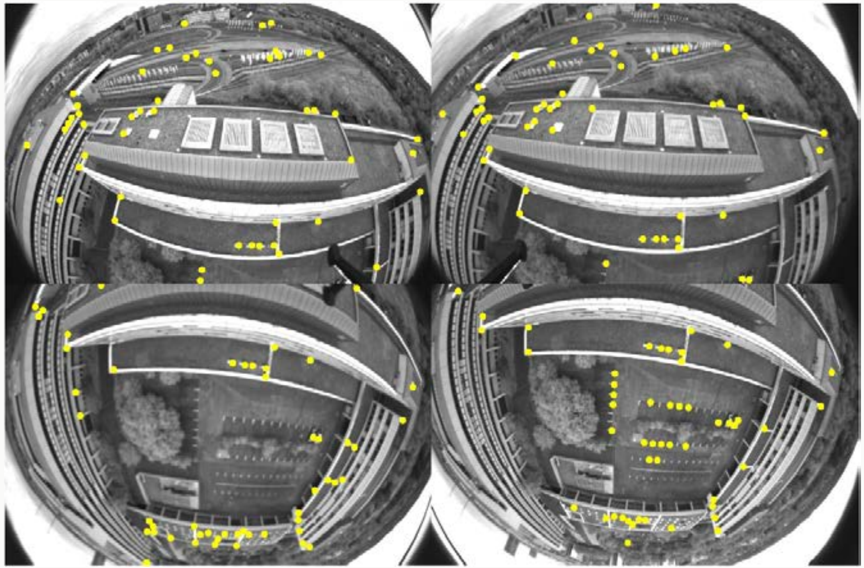
INCREMENTAL BUNDLE ADJUSTMENT (VISUAL ODOMETRY)

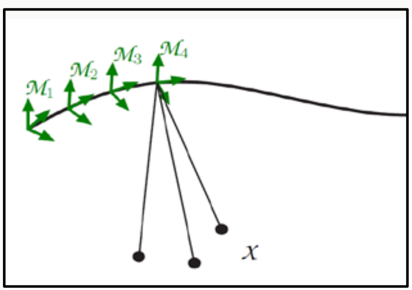


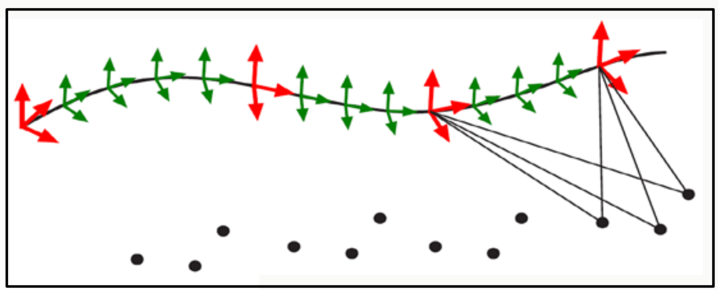
INCREMENTAL BUNDLE ADJUSTMENT (VISUAL ODOMETRY)











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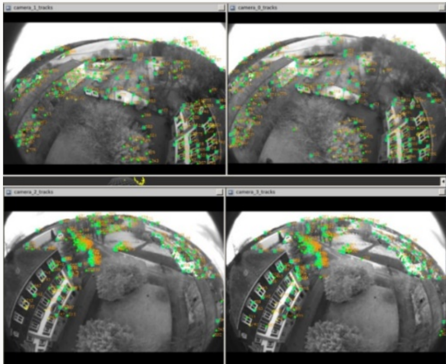
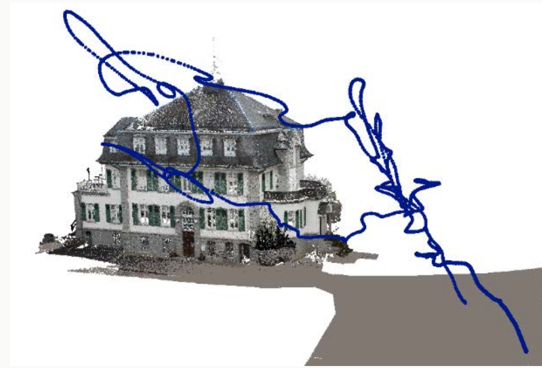
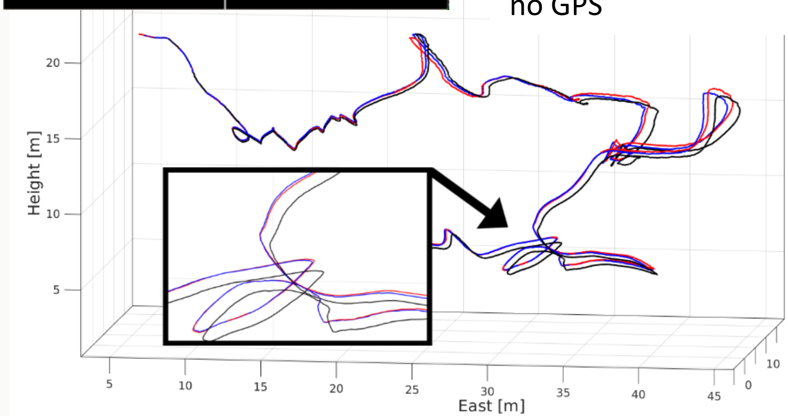
GNSS/ STEREO CAMERA INTEGRATION



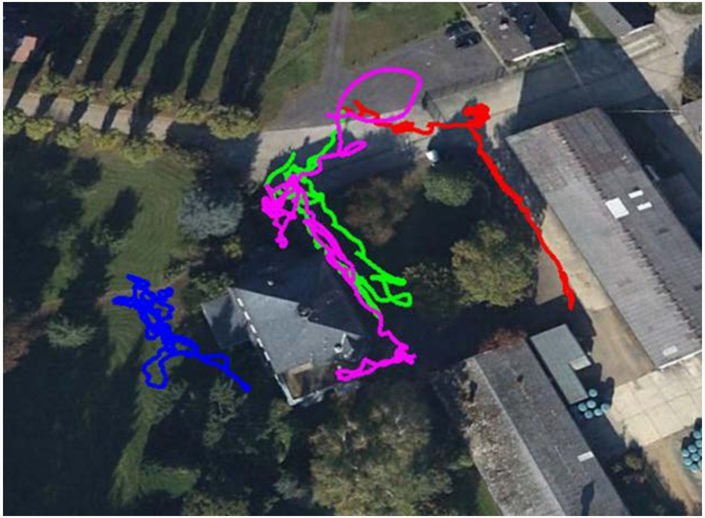


Red: full GPS, Blue: two Satellites, Black: no GPS



- Real-time Visual Odometry based on 4 fisheye cameras (incremental bundle adjustment)
- Tightly-coupled integration of GPS raw observations (double differences) into the adjustment

TESTFLIGHTS



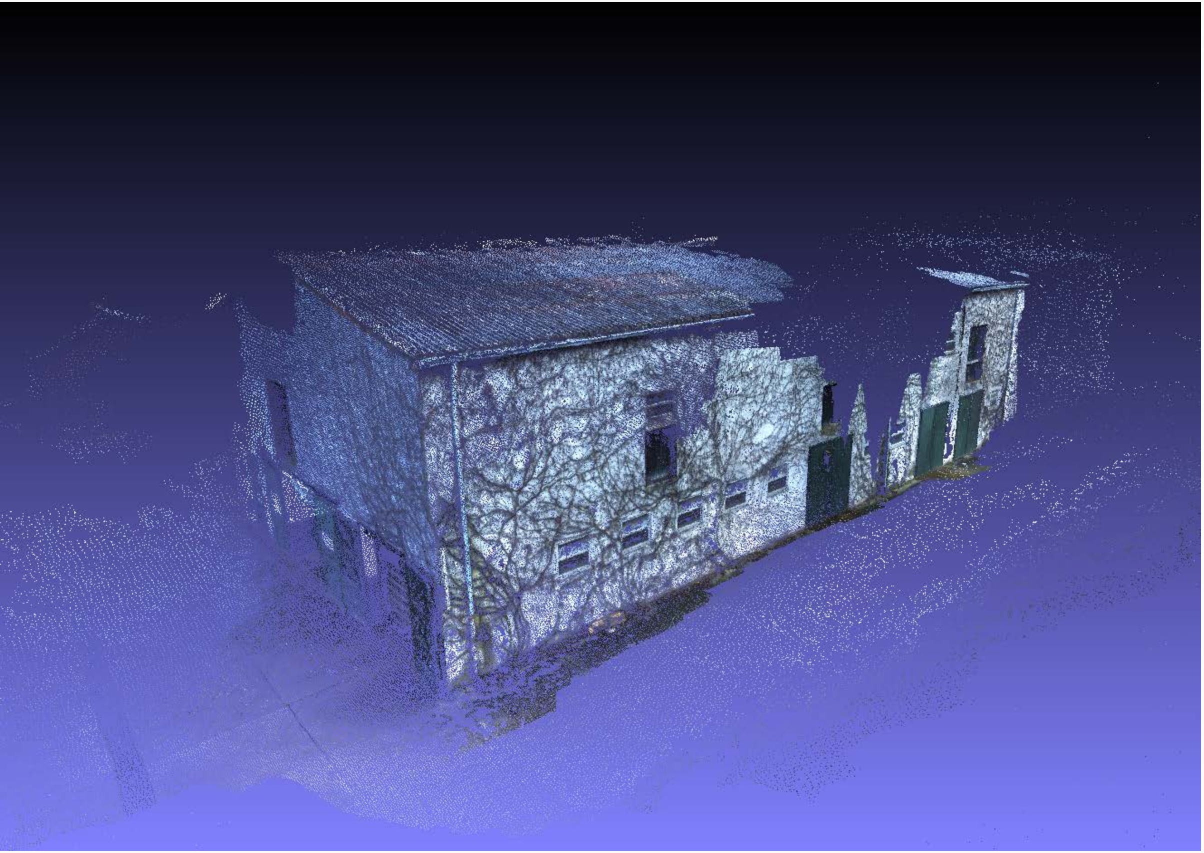
- 4 flights around „Versuchsgut Frankenforst“ near Bonn
- ~5min per flight
- Close to buildings and trees
- Manual control
- On board real time georeferencing
- No control points
- High resolution images @1Hz

Postprocessing:

- Bundle adjustment on high resolution images
- Transformation from photogrammetric trajectory to GPS trajectory
- Dense image matching (PMVS: free software) with oriented images

➔ Georeferenced Point cloud without usage of control points

GEOREFERENCED POINT CLOUDS



GEOREFERENCED POINT CLOUDS

GEOREFERENCED POINT CLOUDS

closer view (the window is open)

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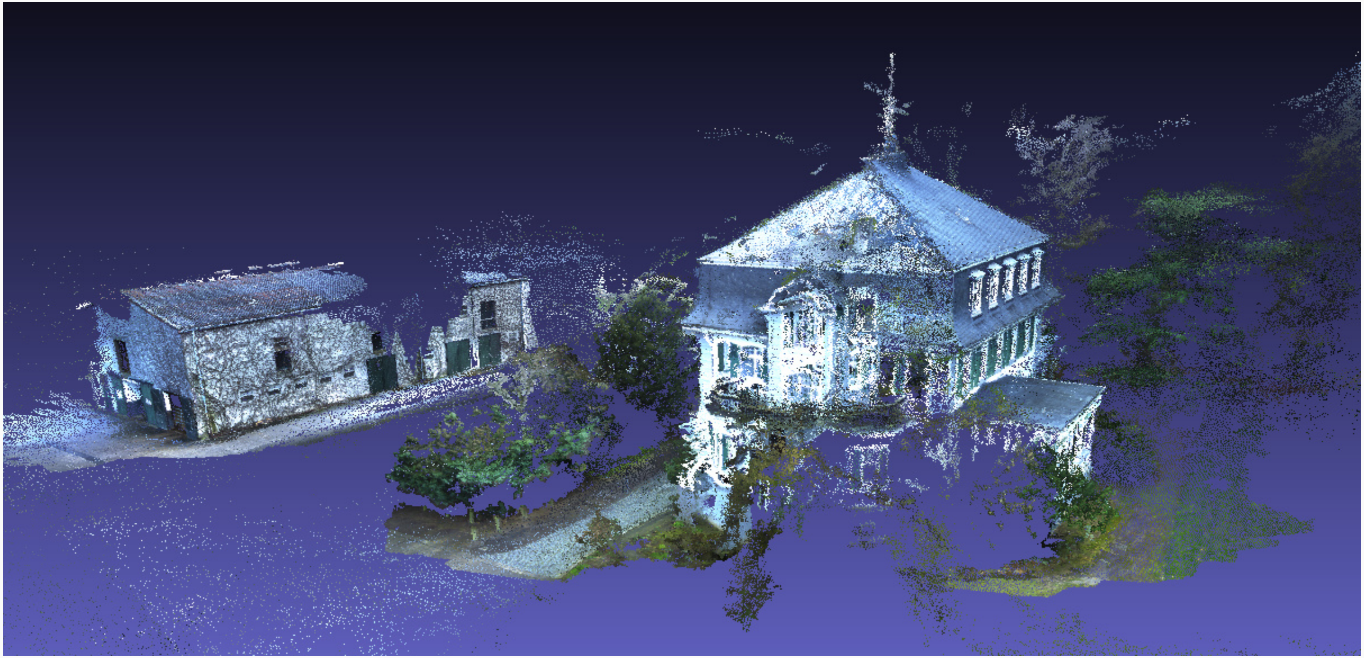
GEOREFERENCED POINT CLOUDS



merged point clouds from 4 flights (no scan registration!)

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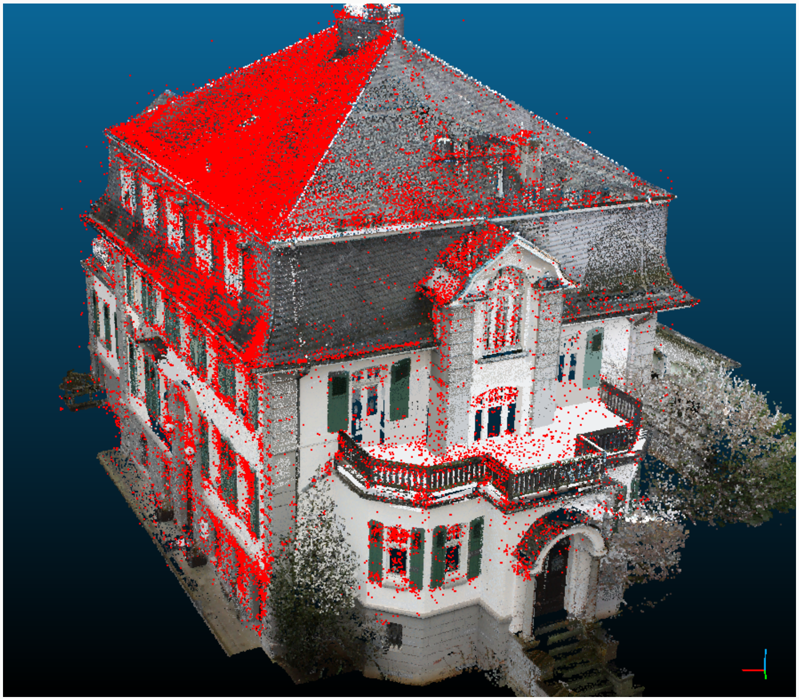
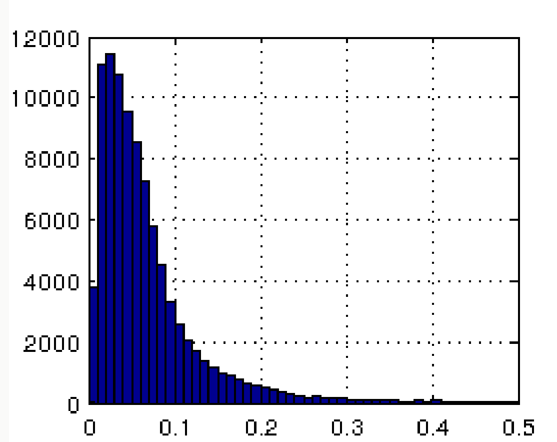
UAV BASED MOBILE MAPPING

ACCURACY ANALYSIS





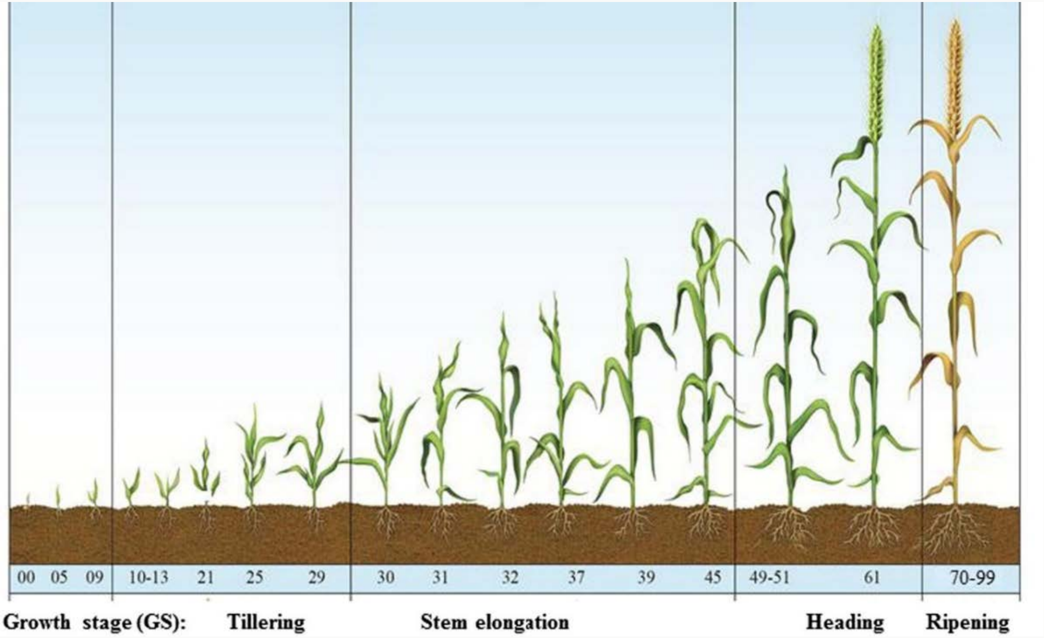
Point to Point distance

(neares neighbour)

Comparison with
Terrestrial Laser Scan

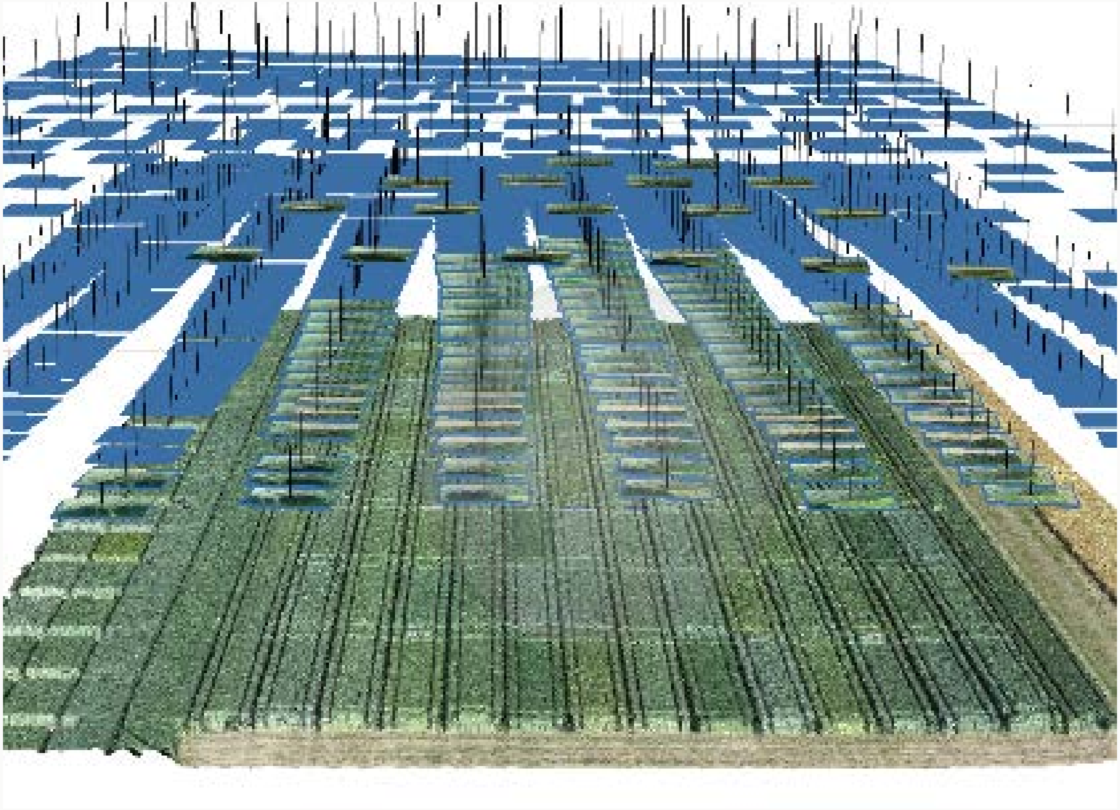
PROJECT EXAMPLE CROPWATCH

- **Goal**: Observe plant parameters (e.g. canopy height) from UAV flights during growing season



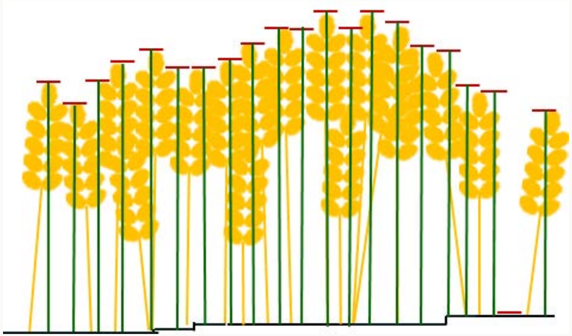
https://ars.els-cdn.com

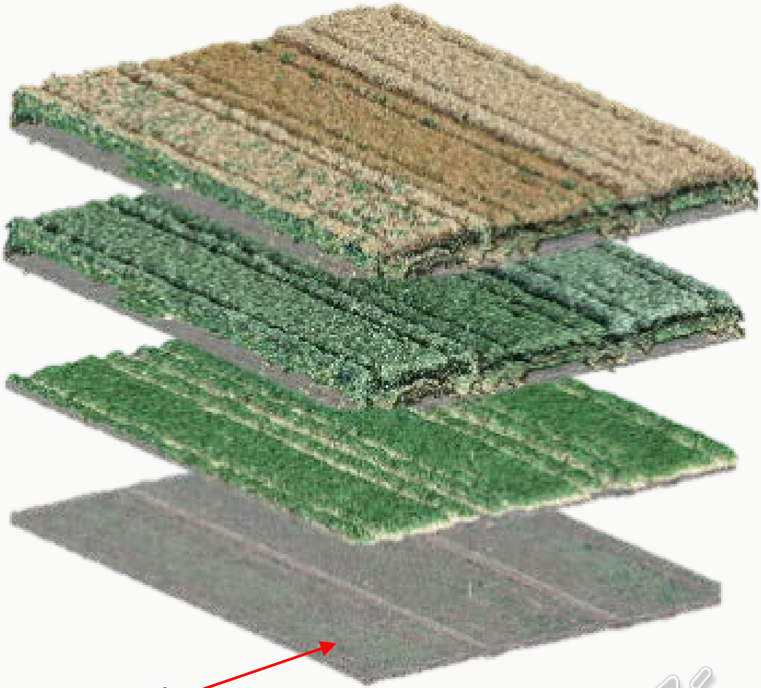
CREATE GEOREFERENCED POINT CLOUDS



UAV BASED HEIGHT MEASUREMENTS

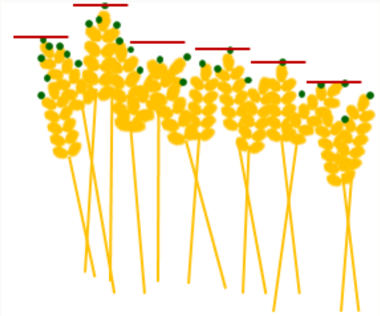
- Measure before emergence and at different dates
- Calculate difference

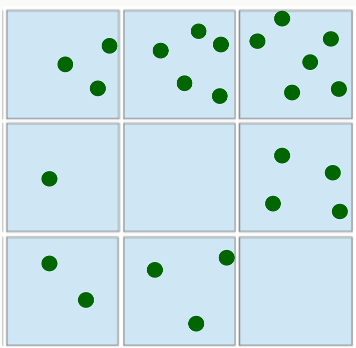




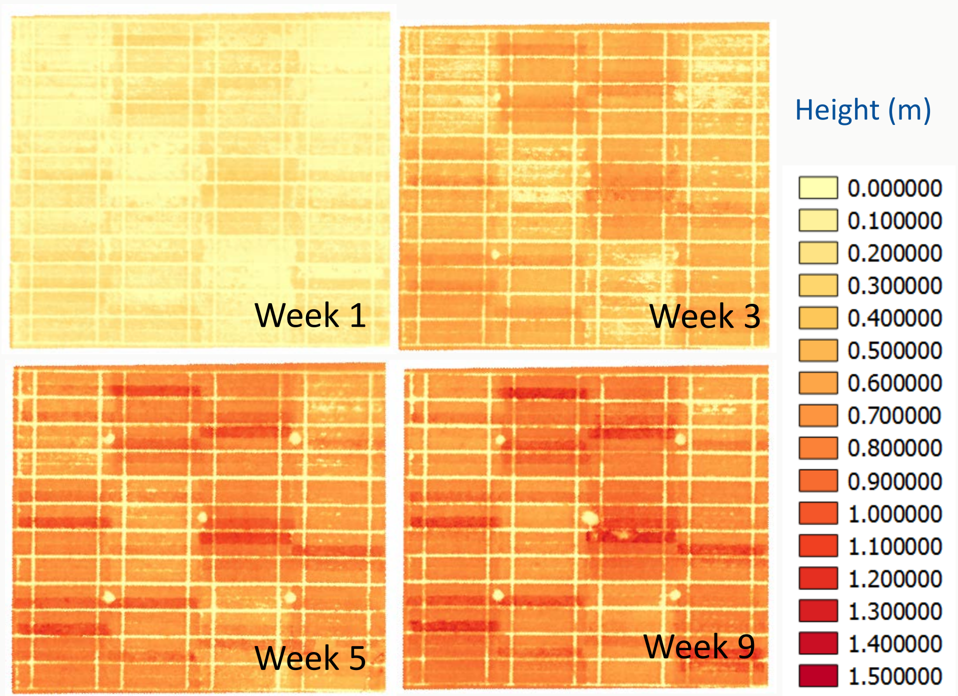
ground

UAV BASED HEIGHT MEASUREMENTS





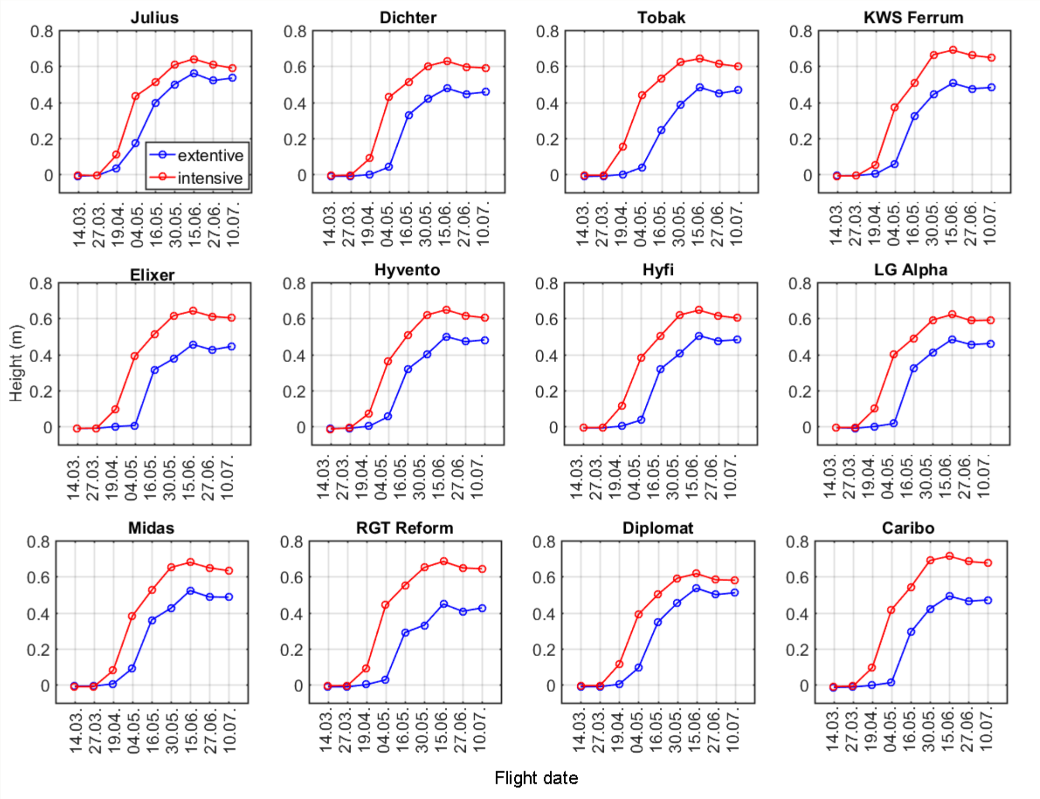
Point cloud data



Height raster

UAV BASED HEIGHT MEASUREMENTS

Intensive vs.
extensive
management



From: Becirevic, D., Klingbeil, L., Honecker, A., Schumann, H., Rascher, U., Léon, J., and Kuhlmann, H.: On the derivation of crop heights from multitemporal UAV based imagery, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., IV-2/W5, 95-102, https://doi.org/10.5194/isprs-annals-IV-2-W5-95-2019, 2019.

IMAGE BASED POINT CLOUDS EXAMPLE

- Building industry, progress documentation

Leica

- Surveying and Mapping

Leica

IMAGE BASED POINT CLOUDS EXAMPLE



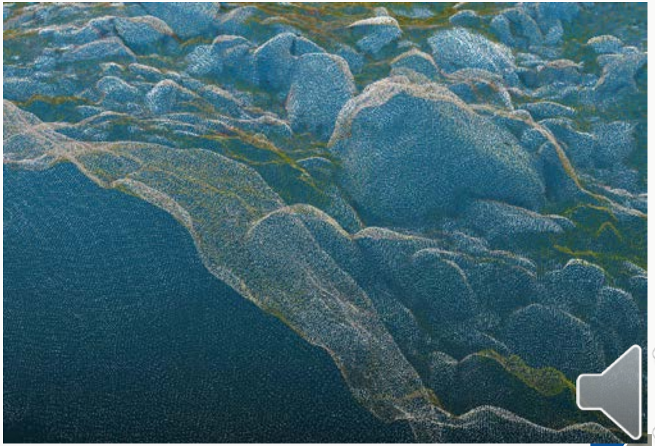



IMAGE BASED POINT CLOUDS EXAMPLE

WHAT YOU HAVE LEARNED TODAY

- How can point clouds be created from images?
- What are the processing steps in a SfM processing pipeline?
- What georeferencing options are there for UAV based mobile mapping?
- How can you calculate the pose of a UAV?
- What are applications for UAV based mapping?

THANKS